

The Utility of Quantum Field Theory¹

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Abstract

This talk surveys a broad range of applications of quantum field theory, as well as some recent developments. The stress is on the notion of effective field theories. Topics include implications of neutrino mass and a possible small value of $\sin(2\beta)$, supersymmetric extensions of the standard model, the use of field theory to understand fundamental issues in string theory (the problem of multiple ground states and the question: does string theory predict low energy supersymmetry), and the use of string theory to solve problems in field theory. Also considered are a new type of field theory, and indications from black hole physics and the cosmological constant problem that effective field theories may not completely describe theories of gravity.

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1 Introduction: Why a Talk on Quantum Field Theory?

Before the advent of string theory, theorists tended to distinguish themselves as “phenomenologists” and “quantum field theorists.” Phenomenologists were rather lowly sorts, who dealt with questions having to do with experiment; the quantum field theorists dealt with “deep” questions such as anomalies and solitons. Presumably this is why it is traditional at this meeting to have sessions on quantum field theory and a summary talk. Today, the dividing line is more between string theory and phenomenology. It is a rare theorist who describes him or herself as a quantum field theorist. There is, however, some logic to having these sessions and this talk. First, quantum field theory is an essential tool both to those interested in phenomenological questions and those interested in the difficult questions of string theory and quantum gravity. Second, despite its current, orphaned status, it remains a subject of great fascination in itself, and great strides continue to be made in its development.

This reasoning gives the speaker license to speak about anything and everything, from phenomenology to string theory, and that is what I will do. Below is an outline of the topics to be covered:

- Quantum Field Theories as Effective Theories
- Quantum Theory and Experiment: The Standard Model
- Quantum Theory and Experiment: Beyond the Standard Model
 - A. Neutrinos
 - B. What if $\sin(2\beta) \approx 0$ (more precisely, what are the implications of a small CP asymmetry in $B \rightarrow \psi K_s$?)
- Applications of Quantum Field Theory to Fundamental Problems in Physics: String (M) Theory
- Applications of String Theory to Problems in Quantum Field Theory
- New Ideas in Quantum Field Theory: Large Dimensions, Non-Commutative Field Theory
- Limitations of Quantum Field Theory: The Cosmological Constant Problem.
- Beyond Quantum Field Theory: Holography

2 Quantum Field Theory as Effective Theory

In the past 30 years, quantum theory has emerged triumphant as the framework in which to describe nature in the very small. At the same time, we have come to view quantum field theories as *effective* theories, valid up to some energy scale. This idea is familiar in the Fermi theory, a theory which breaks down at scales of order 10's of GeV, where it is supplanted by a larger theory.

The development of this viewpoint may account for the current lowly status of these theories, but this is somewhat unfair, because effective field theory accounts for virtually everything we currently understand about nature. The standard model follows from simply postulating a gauge symmetry and particle content. Renormalizability is not a principle to be enforced, but rather the effects of non-renormalizable operators are suppressed by some scale (compare 250 GeV in the Fermi theory), Λ , where some new particles, interactions, or other phenomena must appear. The effects of physics at scales above Λ can be absorbed into the parameters of the effective lagrangian of the low energy field theory.

These ideas have a utility which extends beyond applications to the standard model. They give us a framework in which to understand the limitations of the model, and also the physics which may lie beyond. They also provide powerful tools to understand basic questions which we confront in theoretical physics. By thinking about the low energy behavior of theories which, at a macroscopic level, are very complicated, we have been able, during the last several years, to:

- Make significant progress in understanding field theories themselves. It has proven possible to make exact statements about a variety of field theories, even strongly interacting ones, particularly in cases where the theories are supersymmetric. There are quantum field theories where we can study phenomena such as confinement and electric-magnetic duality in *controlled* approximations.
- Make exact statements about strongly interacting limits of string theory, even though we don't have a non-perturbative setup in which to describe the microscopic theory.

3 The Standard Model as an Effective Field Theory

Physics as we know it has $SU(3) \times SU(2) \times U(1)$ symmetry. There are three generations of quarks and leptons. The unsuppressed (i.e. renormalizable) terms are exactly the gauge and Yukawa interactions of the standard model. In addition, there are a variety of possible suppressed – non-renormalizable – interactions. The most interesting of these – those which we have the best chance of observing – are those which violate cherished symmetry principles, e.g. baryon number, such as:

$$\mathcal{L}_B = \frac{1}{\Lambda^2} QQQ L \quad (1)$$

or lepton number:

$$\mathcal{L}_L = \frac{1}{\Lambda} \phi L \phi L \quad (2)$$

In each case, the question is: what is Λ ? If we are lucky, Λ is not so large that we can't observe the corresponding phenomenon. We have some theoretical guesses: Λ might be the Planck scale or the scale of grand unification. It might be some scale associated with supersymmetry breaking (10^{11} GeV? 10^3 GeV?)

The operator of eqn. 2 gives rise to neutrino masses. The increasing evidence for neutrino masses suggests that Λ is not too small. We might expect, for example, that this operator is suppressed by quark or lepton masses, just as are typical Yukawa couplings. For example, we might guess they are suppressed by y^2 , $y \sim m_\tau/v$, so

$$m_\nu = \frac{m_\tau^2}{\Lambda} \quad (3)$$

In this simple-minded view, neutrino masses suggest that there is a new scale in nature, perhaps at 10^{11} GeV . Of course, without a theory, y can vary over a huge range, and so can Λ . Still, neutrino masses are our first glimpse at a new scale of physics – real physics beyond the standard model.

4 Standard Model and CP Violation?

Shortly before coming to this conference, one of my experimental colleagues asked me what I would think if $\sin(2\beta) \ll 1$. He seemed to believe that I would be very troubled by such a finding, since it is not compatible with the standard model. Instead, my reaction was one of great excitement. First, such an observation would have a natural description in the language

of effective field theory. Second, it would definitely mean that there is new physics, at a not too distant energy scale. Third, various people, myself included, have long proposed that this is quite a reasonable – even likely – possibility, if nature exhibits low energy supersymmetry[1, 2, 3]. Let me explain each of these points.

If $\sin(2\beta)$ is small, then so is the CKM phase. In the limit of vanishing CKM phase, there is no CP violation in the standard model, so there must be some new physics. (In this situation, of course, the measurement of the CP asymmetry in $B \rightarrow \psi K_s$ is not necessarily a measurement of $\sin(2\beta)$, since there are contributions to this process beyond those of the standard model.) In the $K - \bar{K}$ and $B - \bar{B}$ systems, it must be possible to describe the effects of this new physics by operators in the low energy effective lagrangian. An operator such as

$$\mathcal{L}_{\Delta s=2} = \frac{e^{i\phi}}{\Lambda^2} s \bar{d} s \bar{d} + \text{h.c.} \quad (4)$$

for example, could be responsible for ϵ , where Λ , as always, represents the scale of the new physics.

Now suppose that nature is supersymmetric, with supersymmetry broken at a scale $\Lambda = M_{susy} < TeV$. In supersymmetry, there are many new sources of CP violation. CP-violating, $\Delta s = 2$ operators are generated in the low energy theory, for example, by exchanges of gluinos and squarks. The possibility that phases in the squark and gluino mass matrices might be the origin of the observed CP violation has been explored for some time[2], and was discussed by Ko at this meeting[4].

Not only is it *possible* that this is the case, but one might even argue that it is *likely*. The line of argument goes as follows. If nature is supersymmetric with supersymmetry broken near the weak scale, one typically obtains too large a value for the neutron electric dipole moment, unless CP-violating phases are small, of order 10^{-2} . CP violating phases can naturally be small if CP is a good symmetry of the microscopic theory, spontaneously broken at some lower scale. In this case, the KM angle is small. This picture finds support in string theory, where CP is a gauge symmetry, which must be spontaneously broken[5, 6].

The final ingredient in this picture comes from the physics of flavor conservation/violation. In supersymmetric theories, the absence of flavor-changing neutral currents is not automatic; some additional structure must be imposed. In many of the proposals for this additional structure, $K - \bar{K}$ mixing is nearly saturated by supersymmetric contributions, so the supersymmetric contribution to ϵ is automatically of the correct order if the CP-violating phases are of order 10^{-2} (ϵ' can also be accomodated).

So the answer to my colleague is: few things could be as exciting as the discovery that $\sin(2\beta)$ doesn't agree with the Standard Model prediction, and there is at least one well-motivated framework which predicts that $\sin(2\beta)$ should be quite small.

5 The Hierarchy Problem

Thinking about the Standard Model as an effective field theory with a cutoff Λ leads immediately to a puzzle connected with the Higgs field. Dimensional analysis implies

$$m_H^2 = c\Lambda^2, \tag{5}$$

and this is obtained from the Feynman graphs of the effective theory. The fact that $m_H < TeV$ (and is most likely much lighter) suggests that new physics should not be too far away.

Previous guesses about this physics were:

- New Strong Interactions – Technicolor. Here $\Lambda \sim 1TeV$.
- A New Symmetry – Supersymmetry. Here, we expect $\Lambda \sim M_z - 1TeV$.

Of course, one of the likely possibilities has always been: something we have not guessed. In the past two years, there has been extensive exploration of two new possibilities:

- Large extra dimensions. This was the subject of Lawrence Hall's excellent review at this meeting. The basic idea here is that m_H is the fundamental scale; the Planck mass is large because some or all of the extra dimensions are large[7, 8].
- Warped dimensions: here the idea is that the hierarchy of scales results from an exponential dependence of the metric on the distance in an additional dimension[10]. We will discuss this possibility further shortly.

6 Supersymmetry and Our Understanding of Field Theory

Field theories such as real QCD are complex, and it is difficult to extract even qualitative information. In the last few years, however, it has been possible to solve, at least in part, many non-trivial field theories with supersymmetry. Supersymmetry turns out to give a great deal

of mathematical control. This has allowed an attack on basic issues in quantum field theory such as duality and confinement, and on the basic problem of supersymmetry phenomenology: understanding the origin of supersymmetry breaking.

In supersymmetric theories, the coupling constants are often *complex numbers*; the reason one can learn so much about these theories, is that many physical quantities are analytic functions of these numbers.

Supersymmetric gauge theories provide an example of this phenomenon[11]. The imaginary part of the coupling constant is the θ parameter. The low energy effective coupling is an analytic function of the “bare coupling,”

$$\tau = \frac{8\pi^2}{g^2} + i\theta \quad g_{eff}^{-2} = f(\tau). \quad (6)$$

This, by itself, does not allow one to say much. But the the low energy theory is often symmetric under:

$$\tau \rightarrow \tau + 2\pi i \quad (7)$$

(corresponding to the 2π periodicity of the θ parameter). This highly restricts f ;

$$f = \tau + \sum_{n>0} a_n e^{-n\tau} \quad (8)$$

This equation, for example, says there are no corrections to the coupling constant in perturbation theory (the subtle meaning of this statement was made clear in [11], where it was shown how one can compute a β -function to all orders in perturbation theory). Further considerations in some cases determine f completely.

This type of analysis has given control many seemingly impossible problems in supersymmetric field theories. These include:

- Exact solutions of theories with N=2 supersymmetry (Seiberg and Witten[12]). In these theories many quantities can be computed exactly. In the strongly coupled region, for example, one can study confinement as the result of monopole condensation. Further progress in this area was reported at the meeting, including exquisite tests of these ideas (Fucito[13], Khoze[14]) and determination of patterns of symmetry breaking in particular examples (by Murayama[15] and Yasue[16]).

- Theories with N=1 Supersymmetry might provide the solution to the hierarchy problem. Not only do they give a way of understanding why there are not big corrections to the Higgs mass $\Lambda \ll M_p$, but they can naturally produce very large hierarchies. Further progress on such theories was reported at this conference (Kazakov[17], Nitta[18], Tachibana[19]).

7 Applied Duality

Apart from addressing fundamental questions in field theory, we can try to use these ideas to understand, e.g., how supersymmetry might be realized in nature. This is an area which has been developing for some time, but the past two years have seen some interesting new ideas:

- Models with dynamical supersymmetry breaking have been put forward in which the partners of the first two generations of fermions are composite and quite massive, while the partners of the third generation are light[20]. These models, first, implement both the ideas of dynamical supersymmetry breaking and quark and lepton compositeness. They are readily compatible with bounds coming from direct searches as well as processes such as $b \rightarrow s + \gamma$. They are simpler and less contrived than earlier proposals.
- Models in which nature is approximately conformally invariant over a range of energies can address not only supersymmetry breaking, but also provide models of flavor[21]. Yukawa hierarchies arise because fields in different generations possess different anomalous dimensions. Many problems of flavor physics are readily understood in this context.

8 String Theory as a Tool for the Investigation of Field Theory

Over the past several years, it has proven fruitful to consider certain problems in quantum field theory from the perspective of string theory. This is illustrated by simple configurations of D -branes. In Type II string theory, a configuration of N parallel $D3$ branes describes a theory with gauge group $SU(N)$ and $N = 4$ supersymmetry. More interesting models, with less supersymmetry, can be constructed along these lines. Problems which are very difficult from a field theory perspective take on quite a different character (e.g. geometric) in the string picture.

Recent new developments have been based on the “AdS-CFT” correspondence. This correspondence asserts that conformally invariant QFT is equivalent to string theory in AdS space[22]. This can be used to provide insight into a variety of field theories with conformal invariance, but we would like to understand real QCD, which is certainly not conformally invariant. It is necessary to perturb the system in some way.

Early approaches to this problem involved, for example, finite temperature in five dimensions (in the high temperature limit, the system becomes essentially four dimensional)[22]. These methods were of limited power. Recently, Polchinski and Strassler have exhibited cases where one can perturb the conformal theory by adding non-conformally invariant operators, and where the physics on the supergravity side is completely under control (non-singular spaces)[23]. These are theories where confinement, flux tubes, glueballs, and other interesting phenomena can be thoroughly studied in the gravity dual.

9 A New Type Of Field Theory

In the past year, much attention has been focused on a new type of field theory, known as “non-commutative field theory” (NCFT). These theories arise in some cases as the low energy limits of string theories, and seem to incorporate some of the non-locality of string theory[24]. They exhibit bizarre connections between the infrared and the ultraviolet. These features are interesting in themselves, and might be relevant to understanding difficult problems such as the cosmological problem and issues in black hole physics.

The basic feature of these theories is that space coordinates do not commute:

$$[x, y] = i\theta. \quad (9)$$

This sort of relation arises in string theory in the presence of a background magnetic field. NCFT’s can’t be local. They exhibit peculiar connections between the infrared and ultraviolet – which have come to be called the *infrared-ultraviolet* connection. For example, typical Feynman graphs behave as

$$\int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2} e^{i\theta p_1 k_2} \quad (10)$$

For $\theta = 0$, this diagram would be highly divergent in the ultraviolet, but for $\theta \neq 0$, it behaves as $\frac{\theta}{p^2}$. In other words, an ultraviolet divergence gets replaced by a divergence as $p^2 \rightarrow 0$.

It is fair to say that the significance of these theories is only beginning to be understood. Could there be real phenomena which might be described by such theories? Might they give some insight into the cosmological constant problem? Could these structures have relevance to other areas of physics? Time will tell.

10 Field Theory as a Tool for Understanding String Theory

The pictures which have been described above can be viewed from a different perspective: One can hope to use one's understanding of field theory in order to understand difficult questions in string (M) theory. (See the talk of Paul Townsend at this meeting.)

These ideas have a long history. The easiest way to prove the finiteness of string theory is to study the effective field theory. Indeed, even though there is much that we do not understand about the fundamental structure of the theory, many questions can be addressed by considering the low energy field theory limit.

Here are just a few of the areas in which field theory has proven useful to understanding outstanding problems in string theory:

- Much of the understanding of duality in string theory has been obtained from the study of the low energy effective field theory.
- String theory has a host of possible vacuum states which are uncovered in various approximations. These are characterized by the number of dimensions (2-11), the amount of supersymmetry ($N = 0, \dots 4$), the number of generations, as well as sets of continuous parameters ("moduli"). The hope is that some dynamical effects pick out one vacuum or another. From considerations of the low energy effective field theory, however, we know that all of the vacua with some supersymmetry in $d \geq 5$ or with $N > 1$ supersymmetry in $d = 4$ are true, stable vacua of string theory, *exactly*.
- We can make many exact statements about more promising vacua which, in some approximation, have $N = 1$ supersymmetry. We can often compute the ground state energy as a function of the moduli reliably using effective field theory. We can sometimes argue that couplings unify even if the theory is strongly coupled.

11 Unconventional Approaches to Outstanding Problems

11.1 Large Dimensions

In the past two years, two new approaches have been put forth to the hierarchy problem. While the underlying justification for both is string or M theory, both are firmly based on pictures developed by considering the low energy field theory.

The premise of each of these proposals is that the fundamental scale of physics might be close to the weak scale. This obviates the need for supersymmetry as a solution to the hierarchy problem, and, indeed, in both of these approaches, low energy supersymmetry (at least as it is conventionally discussed) is not a likely outcome.

Lawrence Hall has discussed the large dimension possibility at some length at this meeting. The basic idea is that the fundamental scale of the theory is of order a TeV. The Planck scale, in this view, is large because some set of extra dimensions are large. I will not review this proposal in detail here. However, I would like to mention two sets of ideas about supersymmetry breaking which have emerged from thinking about large, but not extremely large, extra dimensions. These start from the idea of two separated walls, with the standard model on one wall, supersymmetry-breaking on another. The first of these is known as Anomaly Mediation[25]. Precursors of this idea arose from four-dimensional, field theoretic reasoning[26]. In this picture, one finds an approximate degeneracy between squarks, necessary to understand the suppression of flavor violating processes. In the simplest version, some sleptons are tachyonic, however, and it is necessary to consider rather complicated models. The second is known as gaugino mediation[27]. Again, this idea has field theoretic precursors[28], but finds a firmer motivation in the large dimension picture. Here, the idea is that certain gauge multiplets propagate in the bulk, and are natural candidates to mediate supersymmetry breaking. Again, this is a way to obtain a spectrum with a suitable degree of degeneracy and other distinct predictions for the low energy soft breakings.

11.2 Warped extra dimensions: The Randall-Sundrum Model(s)

The second of these new proposals to understand the hierarchy problem is known as the Randall Sundrum model. Actually, there are several versions of this model. The simplest to describe is set in five dimensions, with two walls. With the walls as sources of stress-energy, if one tunes

parameters, Einstein's equations admit a solution:

$$ds^2 = e^{-2kr_o|y|} dx^\mu dx_\mu + r_o^2 dy^2 \quad (11)$$

Four dimensions are flat, but the fifth, described by y , is curved, or “warped.” The standard model sits on the wall at $y = 1$; the wall at $y = 0$ is referred to as the “Planck Brane.”

In the effective theory in four dimensions, Newton's constant is given by:

$$G_N = \frac{k}{M^3} \frac{1}{1 - e^{-kr_o\pi}} \quad (12)$$

while the typical scales on our brane are of order

$$m_H^2 = M^2 e^{-2kr_o}. \quad (13)$$

So the hierarchy is due to the warping of space, and it is large because it is the exponential of a rather modest number (compare technicolor, susy approaches). (New solutions of this type were reported at this meeting by Ichinose[29].)

What fixes the separation of the walls which determines the exponential? Goldberger and Wise have shown that it can arise from plausible scalar field dynamics in the low energy theory[30].

There are a number of versions of these ideas currently being explored. These include the possibility that the extra dimensions are infinite, with gravity localized on a brane[31], or that, viewed from far enough away, the extra dimension is simply flat[32]. Surprisingly, these ideas are not easily ruled out, and if correct, these lead to distinctive phenomenologies (reviewed by Hewett at this meeting[33]), with some features in common with the large dimension picture.

It should be noted that this structure, unlike the large dimensions structure, has not been derived from string theory, though there is much effort along these lines.

11.3 An Effective Field Theory Critique

The large dimension and warped dimension ideas are exciting, and are plausible alternatives to supersymmetry as solutions to the hierarchy problem. Experiment might produce a smoking gun for one of them.

On the theoretical side, there are many questions which must be settled. All of these are problems of the effective field theory:

- Proton decay, $\mu \rightarrow e + \gamma$, etc. One can certainly imagine various ways of suppressing proton decay. Refs. [34] provide several proposals, and if these are operative, they provide more than adequate suppression. One can debate whether these are more or less plausible than R-parity, for example, in supersymmetric models.
- Flavor changing neutral currents.
- High precision electroweak experiments.

In each case, one expects operators to appear in the effective low energy theory which contribute at a dangerous level, unless the fundamental scale is sufficiently large. Precision electroweak experiments provided the most model-independent limits on the fundamental scale in the TeV range. This is perhaps troubling for hierarchies, and is reminiscent of some of the problems of technicolor. Scenarios have been proposed to suppress other effects; these are typically tied in to ideas of how the KM matrix, with its various peculiar features, is generated. One possibility is that there is a large flavor symmetry, with symmetry breaking occurring on branes located far from the brane on which the standard model sits[35]. While the original models of this sort were rather elaborate, more elegant models were proposed in [36].

11.4 Solutions to the Hierarchy Problem: A Scorecard

It is interesting to compare the various solutions which have been proposed for the hierarchy problem, and to compare with the minimal standard model. One can score them according to:

- Do they solve the hierarchy problem?
- Do explicit models exist?
- Do they explain unification of couplings in a robust, generic way?
- Can they explain the absence of flavor changing processes in a simple way?
- Do they explain the absence of proton decay in a simple way?
- Do they lead naturally to a dark matter candidate?

I will let you do the scoring yourself (I offered my own at the conference) but I think it is clear that the standard model and supersymmetry score the highest in any such ranking. Still,

nature will ultimately decide. It is hard to imagine anything which would be more exciting than the experimental discovery of extra dimensions; I'll let you choose where to place your bets.

12 Is Low Energy Supersymmetry A Prediction of String Theory?

It is often said that low energy supersymmetry is a prediction of string theory, and indeed string theory rather naturally produces this sort of structure. But the large and warped dimension ideas are plausible alternatives and need not exhibit the states (squarks, sleptons, neutralinos) expected there.

From studies of low energy field theory limit of strings, however, there *is* some evidence that non-supersymmetric states have problems. Fabinger and Horava[37] have shown that many non supersymmetric states of string theory undergo catastrophic decay. This instability is closely related to an instability of the simplest Kaluza-Klein theory, discussed some years ago by Witten[38]. If this problem is generic, low energy supersymmetry is a prediction of string theory.

Are there other problems with non-supersymmetric theories? Perhaps related to the instability discussed above, non-supersymmetric string theories rather typically have tachyons somewhere in their classical moduli spaces. One might imagine that this is not so serious; perhaps there is simply a nearby vacuum. But a little thought shows that the problem is deeper. Even if the potential has a minimum as a function of the tachyon field, the energy associated with this minimum is of order $V_o = -\frac{1}{g^2}$. Since g^2 is dynamical in M theory, the system can attain arbitrarily low energy by moving to small enough coupling.

All of this sounds serious, but with the current state of our knowledge, it is hardly a proof that non-supersymmetric string states don't make sense. We simply don't understand string theory well enough to decide whether it might be possible that the universe sits in a state far from one of the tachyonic states, or that the lifetime of the universe for the catastrophic vacuum decay of Fabinger and Horava is much greater than the age of the universe. It would be interesting to exhibit some sort of disease of the non-supersymmetric vacua, such as an anomaly, which would decisively indicate such an inconsistency. I have spoken about some possible candidates for such anomalies elsewhere, and am currently engaged in a search for examples.

13 Limitations of Effective Field Theory?

13.1 Two Problems for Effective Field Theory

There is growing evidence that the ideas of effective field theory do not apply to gravity. This evidence arises from the study of Black Holes and the problem of the Cosmological Constant.

One of the most exciting recent developments in physics is the observation of what appears to be a non-vanishing cosmological constant, λ . This is a quantity one would think one could compute from particle physics. However, the same sort of dimensional analysis we used before suggests that

$$\lambda = a\Lambda^4 \tag{14}$$

So even if Λ is as small as 100 GeV, we obtain an estimate 55 orders of magnitude larger than the reported observation! (Alternatively, if λ were this large, our horizon would be about 10 cm!)

In field theory, even if, for some reason, there is no cosmological constant at the classical level, one expects a large value for λ quantum mechanically. This is simply because (for weak coupling) one can think of a quantum field theory, as a collection of harmonic oscillators, one for each particle type and momentum \vec{k} . The vacuum energy, which is just the cosmological constant, then gets a contribution from the zero point fluctuations of each oscillator:

$$E_o = \lambda = \sum \int^\Lambda \frac{d^3k}{(2\pi)^3} \frac{1}{2} (-1)^F \sqrt{k^2 + m^2} \tag{15}$$
$$\propto \Lambda^4.$$

(($-1)^F$ is +1 for fermions, -1 for bosons; it arises because, in the case of fermions, rather than considering the zero point energy, one must compute the energy of the filled fermi sea). Supersymmetry might act as some sort of cutoff. If susy were exact, the bosonic and fermionic contributions to this expression would cancel. However, from our failure to observe any supersymmetric particles to date, we know that we can safely take the cutoff to be as large as 100 GeV. So the low energy contribution to the cosmological constant is at least 56 orders of magnitude too large! At our present level of understanding, we must somehow imagine that this is miraculously cancelled (to a part in 10^{56} !) by high energy contributions.

Many attempts to solve this problem have failed. It seems likely that this represents a breakdown of our ideas about effective field theory.

There is a good deal of evidence that the usual rules of quantum mechanics break down near black holes. The problem is connected with Hawking radiation. Hawking showed many years ago that black holes evaporate. If one imagines a black hole created in a pure state, then in the far future, one has a thermal system. One might imagine that this is no different than, say, burning a piece of coal: the original information in the quantum system must be encoded in subtle correlations among the outgoing photons. This, however, turns out to violate our usual notions of *locality*. String theory seems to possess some degree of non-locality, and there is growing evidence that string theory provides a consistent quantum mechanical framework in which to understand black holes.

13.2 The Holographic Principle

From considerations of black hole physics, 't Hooft and Susskind have suggested that in a theory with gravity, there are not as many degrees of freedom in a volume V as we might expect; they argue that a consistent theory of gravity must be *holographic* – the number of degrees of freedom is proportional to the surface area of V [39, 40].

This holographic principle is in many ways mysterious, but it can sometimes be seen to hold in string theory. At low energies, for many purposes, string theory is well described by an effective field theory, but perhaps not for everything?

If these ideas are correct, some important questions in nature cannot be answered by the methods of effective field theory. This might be crucial to understanding not only black holes but also the cosmological constant problem, since it means that there are far less degrees of freedom than in eqn. 15. By itself, however, the holographic principle does not answer the question of the cosmological constant. Apart from conceptual issues, there is a numerical one. Even if the cosmological constant is suppressed from some naive estimate, say 10^8GeV^4 , by a factor of the current horizon in Planck units, we still miss the observed value by more than 10 orders of magnitude!

14 New Ideas About the Cosmological Constant

Can field theory in four dimensions resolve the cosmological constant problem?

Through the years, a number of ideas have been put forward:

- Perhaps the dynamics of a light particle cancels the cosmological constant, in a manner reminiscent of the axion solution of the strong CP problem? There have been many attempts along these lines, but Weinberg has proven a no go theorem which shows that this cannot occur, at least in conventional field theories[41].
- Interesting gravitational dynamics such as Euclidean wormholes[42] have been proposed, but are not completely satisfactory.

In the last few years, a number of new ideas have been put forward.

- Kachru and Silverstein[43], motivated by the AdS/CFT correspondence, have exhibited a number of string models without supersymmetry in which the cosmological constant cancels at low orders of perturbation theory, and have argued that this cancellation may be general. The known examples, however, have Fermi-Bose degeneracy and it is not clear whether or not this is an essential part of the proposal.
- As noted above, the notion of holography is likely to have some implications for the cosmological constant problem, but it is not clear, at present, precisely what those implications might be. Moreover, while the present horizon is very large, it is not large enough:

$$d \approx 10^{10} \text{ light years} \tag{16}$$

so $d \times (100\text{GeV}) \sim 10^{36}$ (we need about 10^{55}). Still, there have been some interesting suggestions about how this might work[44].

- Warped geometries: there have been a number of suggestions that the gravitational equations in this framework permit solutions with vanishing four dimensional cosmological constant, going back to[45], and more recently [46]. But troubling singularities appear, and it is not yet clear whether these solutions make sense. It has been argued that these singularities are at best just a rephrasing of the fine-tuning problems[47]. This problem is under intense investigation.

15 More Embarrassing Proposals

15.1 What are we trying to explain?

If recent observations of a cosmological constant are correct, then the value of the constant is just such that the cosmological constant is becoming important in the present epoch of cosmic

history,

$$\Omega_\lambda \approx 0.7 \Omega_{crit} \tag{17}$$

In thinking about λ , there is a piece of numerology about the cosmological constant which is often invoked:

$$\lambda \approx \frac{(\text{TeV})^8}{M^4}. \tag{18}$$

Here M is the reduced Planck mass, $M \approx 10^{18}$.

So if we had a theory in which this relation held, we would have Ω_λ in the right ballpark. But while the order of magnitude is correct, we are confronted today with a very close coincidence. If we change TeV to 2.7 TeV, for example, in this formula

$$\Omega_\Lambda \approx 10^3 \Omega_{crit} \tag{19}$$

So even if we had a theory in which 19 held, we would still be confronted with a significant puzzle.

15.2 The Anthropic Principle Rears Its Ugly Head

These remarks are suggestive of an anthropic explanation of the cosmological constant. I believe that the only scientifically defensible form of anthropic explanation is what Weinberg calls the “Weak Anthropic Principle.” Suppose a theory has many metastable (or stable) ground states. The universe in its history may sample all of these states. Only some may develop in a way which can allow for even rudimentary forms of life; most might collapse, for example, long before structure can form.

Even within this framework, as we will see, we are treading on dangerous ground. As Weinberg has remarked: A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you’re against it, some people will think you’re a little too interested.

How would we apply this sort of weak anthropic explanation to the cosmological constant? For this to make sense, the underlying theory must have lots and lots (10^{120} = zillions and zillions – to borrow a phrase from Carl Sagan) of reasonably stable ground states. We live in one with a small cosmological constant because that’s the only place intelligent beings can evolve.

Weinberg originally argued that this sort of weak anthropic explanation was not good enough to explain the cosmological constant; this could only explain why $\Omega_\Lambda < 10^2 - 10^3 \Omega_{crit}$ [41]. Garriga and Vilenkin have argued that a more refined argument gives the right order of magnitude[48]. So we have to face the possibility that this *might* provide an explanation of the observed facts.

Whether you like this sort of explanation or not, we need to ask: do we know of any theories with these properties? The short answer is no, but recently Bousso and Polchinski, and Donoghue have pointed out a way in which such a vast set of metastable states might arise in string theory[49, 50]. The analysis is based on considerations of effective field theory, and in particular of certain gauge fields with three indices, $A_{\mu\nu\rho}^{[i]}$, whose flux is quantized (compare monopoles):

$$F_{\mu\nu\rho\sigma}^{[i]} = q^{[i]} n^{[i]} \epsilon_{\mu\nu\rho\sigma}. \quad (20)$$

The vacuum energy takes on values:

$$E = \sum_i^N n^{[i] 2} q^{[i]} - \lambda_o \quad (21)$$

where λ_o represents the other contributions to the cosmological constant. The number of states grows rapidly with N ; Bousso and Polchinski argue that if $N \sim 120$, for example, there may a sufficient number of states.

Whether these states actually exist as (meta)stable states is an open question, but within our current understanding, we must acknowledge that it is conceivable. When one delves further into this type of picture[51], one finds that in some versions, everything in this suggestion becomes anthropic. In others, it is only the cosmological constant. Determining whether such a vast set of states truly exists is a problem which cannot be settled in effective field theory.

15.3 A Much Milder Use of the Anthropic Principle?

Whether or not string theory has the vast set of metastable states required for the application of the anthropic principle, it is certain that it contains a large number of ground states, only a small fraction of which – if any – resemble the real world. We have already noted that string theory definitely contains states with more than four dimensions and more than four supersymmetries. A milder application of the anthropic principle might be to understand how nature selects among these possible vacua. It could be that in most of them, one can not

develop even the most minimal structures one would imagine are necessary to sustain life, and in fact that many of them would be subject to gravitational collapse. We are a long way from being able to answer this question completely, but partial (positive) answers can already be given, using methods of effective field theory[51].

16 Conclusions

Field theory continues to enjoy an extraordinary level of utility. It gives the standard model, and suggests possible extensions and new phenomena. It gives a way of organizing our questions about new experimental discoveries, and suggests possible explanations. It suggests broad ranges of new phenomena. It is a crucial tool in our study of candidates for a fundamental theory.

Yet field theory also has limitations. We probably need to go beyond quantum field theory if we are to understand:

- The problems of Black Holes
- The Cosmological Constant Problem
- The principles which determine the ground states of M theory, and what selects among them.

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